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Community-identified key research questions for the future of UK afforested peatlands

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SUMMARY

Large areas of UK peatland were planted with non-native conifers in the twentieth century, changing many aspects of the ecosystem. As these plantations reach harvesting age there are important questions about what should be done with them next, with key options including restocking for continued forestry and restoration. Making decisions on the future of these sites is difficult and the underlying evidence base is often incomplete. In order to prioritise future evidence needs we conducted a two-phase consultation exercise to identify what a large body of stakeholders in science, policy and practice consider to be the most important outstanding research questions. The five most popular questions identified were: *How does the greenhouse gas balance of peatland forestry differ between deep and shallow peat and compare to forestry on mineral soils?*; *How does the greenhouse gas budget of a peatland change with initial afforestation, restocking or restoration?*; *Is it possible to have trees on peat without loss of biodiversity and carbon storage?*; *What are the limits to the achievability of forest-to-bog restoration in terms of factors such as peat condition, depth and site extent?*; and *What is the financial value of natural capital in natural and afforested peatlands and how does this change with restoration?* Notable subsidiary themes included flooding, biodiversity and compensatory planting. These questions form potential foci for future research and particularly emphasise the importance of understanding carbon cycling in afforested peatlands.

KEY WORDS: carbon, climate, forestry, forest-to-bog restoration

INTRODUCTION

Peat covers more than a tenth of the UK land surface (Montanarella *et al.* 2006, Lindsay 2010), but large proportions have been damaged by drainage and poor land management. Around 15 % of the total peatland area was ploughed and planted with non-native conifer species in the twentieth century (Payne & Jessop 2018). Globally, many areas of peatland are naturally forested, but this is not the case in the UK where the majority of peatland is believed to be naturally treeless. Forestry on peat was promoted by the desire for secure domestic timber supplies and to stimulate economic activity in rural areas. Afforestation was further accelerated by a favourable tax regime which made afforestation a financially attractive proposition (Stroud *et al.* 2015, Sloan *et al.* 2018). By the 1980s attitudes to peatland forestry had begun to change due to concerns about undesirable impacts, particularly on birds (Warren 2000, Stroud *et al.* 2015). In 1988 the tax incentives which promoted afforestation were abolished by the government and large-scale new afforestation of deep peat was subsequently prohibited by Forestry Commission guidance (Patterson & Anderson 2000, Sloan *et al.* 2018).

There is now considerable uncertainty regarding the future of these peatland plantations as they reach harvesting age. Peatland forestry can have significant economic value but in the UK there has been a strong movement towards peatland restoration over the last decade (Bain *et al.* 2011, Morison 2012). The UK government has ambitious targets for areas of peatland restoration and large investments are being made through public, charitable and private sector funding sources (Bain *et al.* 2011, Andersen *et al.* 2017). It is clear that there are considerable gaps in the evidence base on which future land-use decisions need to be made and a requirement for evidence needs to be codified and prioritised in order for research effort to be directed to where there is greatest need.

In this study we assembled a prioritised list of community-identified outstanding research questions based on the views of stakeholders in science, policy and practice. Previous similar exercises have proved valuable i) for policy-makers, to shape a research agenda which meets their needs; ii) for research funders, to guide research in applied directions which meet stakeholder requirements; and iii) for individual researchers, to improve the 'impact' of their research

(Sutherland *et al.* 2006, 2009, 2011, 2013; Seddon *et al.* 2014).

In this article we describe the process used to identify these questions, itemise the questions that were most highly rated by the community, and discuss the context and background to the most highly ranked questions.

METHODS

Study design

In designing the study we aimed to follow the key principles of Sutherland *et al.* (2011) of openness, inclusivity and democracy. Our study comprised five phases: i) recruitment of participants; ii) an open call for questions; iii) editing of submitted questions by the project team; iv) prioritisation of questions by participants, and v) compilation of the final list of questions. Our study design differed from many previous similar exercises in being conducted solely online. This was partially determined by cost and timescale but had the advantage of being a more democratic option (Wright 2005). Online participation imposes fewer financial or other constraints on participant involvement, ensures complete anonymity if desired, and all participants are able to make equal contributions without the risk of discussions being dominated by a few individuals. Previous studies have found that online survey responses to open-ended questions tend both to be more detailed (Schaefer & Dillman 1998) and to include more self-disclosure (Locke & Gilbert 1995).

Identification and invitation of participants

In inviting participants we aimed to solicit the opinions of all individuals with a stake in the debate about the future of afforested peatlands including those in commercial organisations, public bodies, charitable organisations and research providers. We first assembled a list of email addresses of known interested parties including commercial forestry companies and forest managers; Forestry Commission representatives; peatland conservation managers; peatland specialists in national agencies; scientists active in this research area; environmental consultants; land owners; land managers and relevant private companies such as water supply and wind farm companies. We also included all members of three previously established groups of representatives: the authorship team of the IUCN Commission of Enquiry chapter on forestry; the Scottish National Peatland Committee and the Scottish National Peatland Research and Monitoring Group. This list comprised 124 individuals or organisations. To avoid interested parties being overlooked, participants were encouraged to forward the survey to others and the project was publicised on social media (Twitter) - an approach which has been utilised in other similar studies (Seddon *et al.* 2014). We did not attempt to solicit the views of members of the general public without a professional interest in the subject.

First stage survey

Our open call for questions (the ‘first stage survey’) was made using an online form which was designed to be clear, simple and quick to complete. The survey posed only two questions, the first of which was designed simply to assess the representativeness of the population sampled by asking participants to select their employer or interest in afforested peatlands from a range of options. The second question asked participants to nominate what they considered to be the key research questions, using the wording “When deciding the future of afforested peatlands, what is the most important outstanding question?”. The survey was anonymous and participants were provided with an information sheet which detailed the context of the study and how the data would be used. A briefer summary of this information was included in the form itself and in the soliciting email. The study design and materials were approved by the Ethics Committee of the Environment Department, University of York.

Question re-formulation

Not all questions submitted in an exercise of this nature will be useful in the form in which they are submitted, so an editing phase is typically required. Some questions may be too vague to be directly answerable; some may be off-topic; the answers to some may already be known but not to the contributor. Sutherland *et al.* (2011) propose general principles for useful output which were provided to contributors, but many submitted questions did not conform. Common issues included statements not phrased in the form of a question, questions which included an extensive preamble, and replicated questions. Editorial changes were made by the project team to improve question formatting and remove replication which would otherwise lead to ‘dilution’ of votes between multiple similar questions. We first allocated all the submitted questions to one of eight themes. We then attempted to identify unique topics within these themes and reformulated questions to address the topics using wordings from the original submissions when possible. We aimed to avoid multiple similar questions but to preserve all unique topics amongst the original submitted questions with the exception of i) off-topic submissions; ii) questions which primarily reflected value judgements rather than evidence needs; and iii) questions which were so broad that they covered all the key themes without the scope to offer a suite of questions. All these changes were itemised and the edits communicated to participants as part of the invitation for the second stage of the survey.

Second stage

Participants were invited to participate in the second stage through the same combination of a targeted email list and an open call using social media. The second stage survey had a similar structure to the first. All participants were asked their background and to confirm they had a professional interest in the subject. Participants were then asked to select up to five of the nominated questions which they considered most important. The nominated questions were randomly shuffled to avoid order bias in results (Perreault 1975, Krosnick & Alwin 1987). Finally, we tallied all votes and identified the questions with greatest support within the community.

The first stage of the survey was open for ten days and the second for thirteen days; previous studies suggest that these periods are sufficient to expect most likely respondents to reply (Schaefer & Dillman 1998).

Further details of methodology are available in a report on the website of the Valuing Nature programme of the Natural Environment Research Council (Payne & Jessop 2018).

RESULTS

First stage

In the first stage of the survey, 126 questions were submitted by an unknown number of participants. Particularly common topics identified at this stage were changes in greenhouse gas budgets with restocking and restoration (29 submissions) and compensatory planting for plantations removed for restoration (10 submissions). These 126 submitted questions were edited to 29 questions reflecting unique topics. This process was inevitably subjective and some nuance intended by the original contributors may have been lost; however, we consider that the nominated questions successfully captured the key themes from the submissions.

Second stage

Three hundred and twenty-three votes were cast by 67 contributors in the second stage of the survey with one voter excluded on the basis of answering ‘no’ to the question asking participants to confirm a professional interest in the subject. Relative to the initial invitation list the response rate was 55 %, although an unknown proportion of respondents may have been derived from social media and email forwarding by invitees. Participants represented a wide span of interest groups and respondents were not dominated by any one sector (Figure 1). The most frequent ‘background’ categories selected were forestry sector, governmental/statutory bodies, research organisations and charitable sector conservation groups.

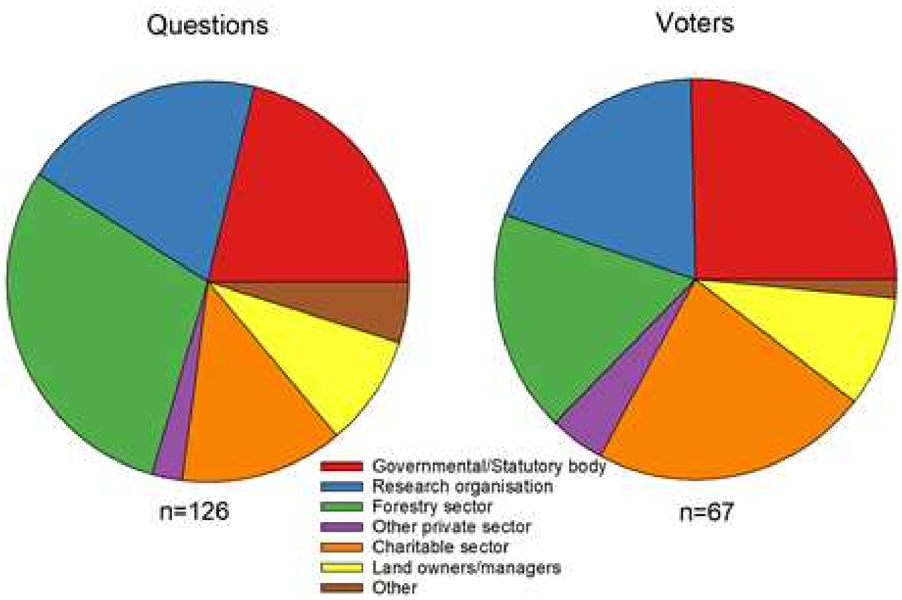

Figure 1. Representation of different sectors (see key) amongst initial question contributors (left) and voters in the second stage survey (right).

There was broadly similar representation amongst question contributors (first stage) and voters (second stage) with a somewhat greater proportional representation from the forestry sector amongst question contributors and from charitable sector conservation organisations amongst voters.

Questions selected

All nominated questions received votes. The most voted-for question and one of the equal second most voted-for questions were both on the theme of greenhouse gases (Table 1). In terms of the eight general themes we identified in the submitted questions, most votes were assigned to the themes of greenhouse gases (89 votes), forestry (64 votes) and restoration (62 votes) with other topics receiving considerably fewer (≤ 38). In our discussion we focus primarily on the five most highly voted-for questions but we also note that other questions were popular amongst specific sectors; for example, questions on flood risk amongst participants from statutory bodies and on biodiversity recovery amongst participants from charitable conservation bodies. We also note that the issue of compensatory planting was popular amongst question nominators, but less so in final voting.

DISCUSSION

Advantages and limitations of the study

While it is difficult to quantify what a truly representative sample of parties with professional interests in afforested peatlands would look like, our respondents clearly constitute a substantial sample of individuals, backgrounds and opinions. Our impression is that the sample is broadly representative, with perhaps slight under-representation of the private forestry sector. The questioning was at the level of individuals and it is possible the results may have been somewhat different if we had asked for unified organisational responses. Overall, we believe the questions identified in this exercise provide a good overview of what stakeholders in science, policy and practice believe to be the most important evidence needs for the future of UK afforested peatlands.

Five key questions

In this discussion we place the five most highly-rated questions in context and assess why an evidence need has arisen. For each question we discuss the context to the question, the current state of knowledge, and what further research might be needed to provide an answer. The questions are discussed in descending order of votes received, with those receiving most votes first. We discuss the first two questions collectively as they consider similar topics and were the first and equal second most voted-for questions.

How does the greenhouse gas balance of peatland forestry differ between deep and shallow peat and compare to forestry on mineral soils?(1st);
How does the greenhouse gas budget of a peatland change with initial afforestation, restocking or restoration? (equal 2nd)

The climate change consequences of alternative land uses is currently a major issue in UK policy and science (Rounsevell & Reay 2009, FLUFP 2010). This is particularly the case for peatlands, where climate change mitigation is a primary driver for current enhanced efforts to restore, conserve and improve the management of sites (Bain *et al.* 2011, Bonn *et al.* 2014). However, current understanding of the climatic consequences of peatland afforestation and restoration is far from complete. As yet it is impossible to say with confidence even whether afforestation exacerbates or ameliorates climate change and certainly not possible to robustly answer questions about restoration and the differences between deep and shallow peat. Current knowledge does allow a reasonable assessment of many of the processes (Figure 2) which affect the greenhouse gas budgets of peatlands with afforestation and restoration. The key gap is around their relative importance (Morison 2012).

Considerable loss of carbon can be expected to have occurred during initial ground preparation and planting. Ploughing will have directly exposed deep, anoxic (catotelm) peat to oxidation in plough-throw ridges and it is likely that there were large fluxes of dissolved and particulate carbon as plant material and exposed peat were disaggregated and decomposed following planting. Carbon fluxes during planting may also have been considerable, however, as no monitoring was undertaken at the time and new afforestation on deep peat is no longer permitted (Forestry Commission Scotland 2015) these fluxes are now difficult to quantify. One way this could be addressed is through carbon stock comparison studies which integrate all losses and gains of carbon over time.

In the period following initial ground preparation and planting, longer-term water table drawdown will have exposed a greater depth of peat to oxidative decomposition (Lindsay *et al.* 2014). There is a well-understood positive correlation between peatland water table depth and CO_2 efflux (Moore & Knowles 1989) and it is probable that afforestation will have increased CO_2 production and most likely also

Table 1. Nominated questions and full votes in our survey of key questions. The five most voted-for questions are in **bold** type. Results are shown in aggregate ('all') and by sectors. Key to sectors: G = governmental / statutory body; R = research organisation; F = forestry sector; P = other private sector; C = charitable sector; L = land owners / managers; O = other.

Identified question	Sectors							
	All	G	R	F	P	C	L	O
How does the greenhouse gas balance of peatland forestry differ between deep and shallow peat and compare to forestry on mineral soils?	21	7	3	6	1	1	3	0
How does the greenhouse gas budget of a peatland change with initial afforestation, restocking or restoration?	20	5	6	2	1	4	2	0
Is it possible to have trees on peat without loss of biodiversity and carbon storage?	20	3	5	6	2	2	1	1
What is the financial value of natural capital in natural and afforested peatlands and how does this change with restoration?	18	6	1	7	0	2	2	0
What are the limits to the achievability of forest-to-bog restoration in terms of factors such as peat condition, depth and site extent?	18	4	4	4	1	4	1	0
How will the water quality of peatland catchments be affected by continuing forestry or restoration?	16	6	3	2	1	4	0	0
Is it possible to restore afforested peatlands to naturally functioning systems and how long will this take?	15	3	4	1	1	5	0	1
How can restoration sites be optimally managed to ensure rapid recovery of natural peatland functioning?	15	5	2	1	0	6	1	0
How should afforested peatland sites be prioritised for restoration and when is the best time to restore?	14	3	3	1	2	4	1	0
How do afforested peatlands and peatland restoration affect downstream flood risk?	14	7	1	1	1	4	0	0
How does the peatland greenhouse gas balance change across multiple rotations of forestry?	13	3	3	5	0	1	1	0
How appropriate are current emission factors for UK afforested peat?	12	2	4	1	0	4	1	0
Should peatland plantations removed be compensated by additional forestry on mineral soils, where should these plantations be located, and what are the opportunities and costs of doing this?	12	2	2	4	0	2	2	0
How will biodiversity recover with forest-to-bog restoration in the long-term?	12	2	2	0	0	8	0	0

Identified question	Sectors							
	All	G	R	F	P	C	L	O
Why are naturally forested peatlands so rare in the UK, were they more abundant in the past and would understanding their decline help us better manage current afforested peatlands?	12	1	4	2	0	5	0	0
How will climate change affect the sustainability of forest-to-bog restoration?	11	1	1	5	0	1	2	1
Is knowledge of peatland extent, depth and carbon stock adequate to make policy decisions on the future of afforested peatland?	10	2	2	1	1	3	1	0
How could private sector land owners be incentivised to restore afforested peatlands and would this be desirable?	10	3	0	1	1	4	1	0
How will climate change affect peatland forestry?	10	5	2	1	0	0	2	0
How far beyond a plantation does forestry affect the greenhouse gas balance of unplanted peatland?	8	1	3	1	1	2	0	0
How does peatland hydrology change with afforestation and restoration?	8	2	2	0	0	3	1	0
How do alternative forest management practises affect greenhouse gas balance?	7	1	3	1	0	0	2	0
How does greenhouse gas balance of afforested peat vary with forest yield class?	7	2	2	1	0	1	1	0
What are the economic benefits of forestry on peat and how do these compare to restoration and forestry on mineral soils?	7	2	0	3	1	0	1	0
How can timber be harvested from peatlands with minimal environmental disturbance?	6	1	1	1	0	2	0	1
How can afforested peatlands be made as natural as possible?	5	1	2	0	0	1	1	0
If replanting on peatland is not allowed should private sector investors be financially compensated and how could this be achieved?	2	1	0	0	0	0	1	0
How does forestry yield relate to peat depth?	2	1	0	1	0	0	0	0
How long will it take for the carbon from felled peatland plantations to be returned to the atmosphere?	1	0	0	0	0	0	0	1
Could the planting or maintenance of peatland forests be justified to mitigate erosion?	1	0	0	1	0	0	0	0

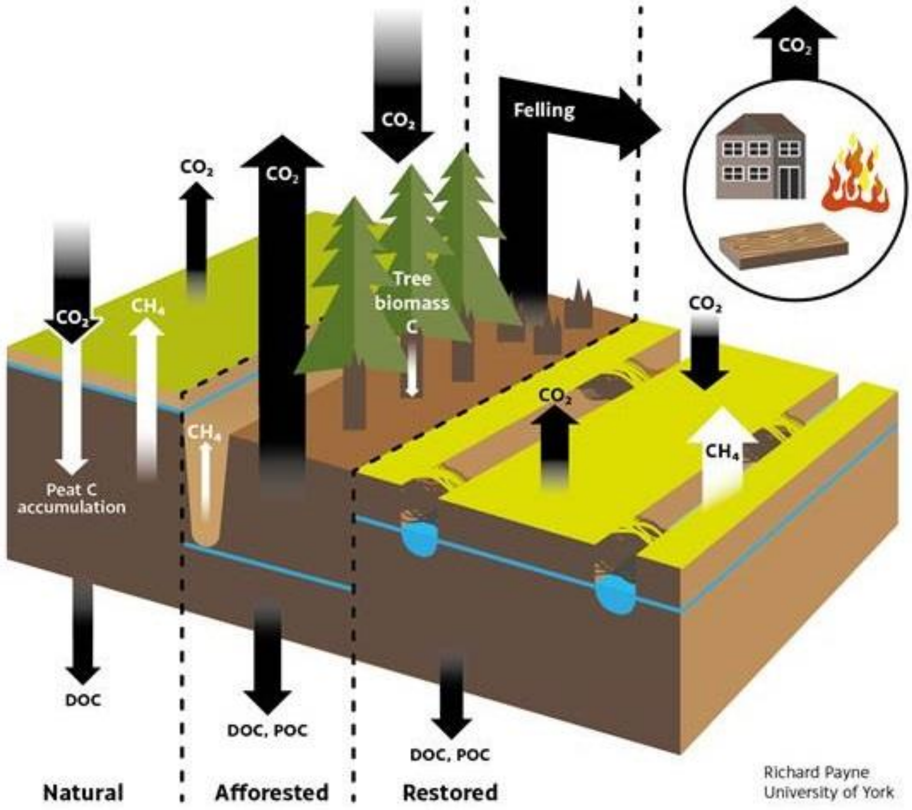

Figure 2. Conceptual diagram of key carbon cycle pathways and changes with peatland afforestation and restoration. Note that there is considerable uncertainty about the relative scale of many of these processes so the sizes of the arrows should be regarded as indicative at best.

increased DOC loss. A corollary of increased CO_2 emission from peat drained for forestry is a likely reduction in CH_4 emission (Vanguelova *et al.* 2018). Water table drawdown is likely to have increased the potential for methanotrophy and there is also likely to have been a reduction in abundance of plants with aerenchyma which are disproportionately important in channelling CH_4 to the atmosphere (Shannon *et al.* 1996). Typical bog species are known to decline or disappear following afforestation and afforested sites are therefore unlikely to form new peat. Considerable quantities of needle and wood litter may accumulate, but the long-term stability of this carbon pool is uncertain (Hargreaves *et al.* 2003, Vanguelova *et al.* 2018). Forested peatlands with greater nutrient supply can also be substantial sources of N_2O (Huttunen *et al.* 2003) and forestry may change albedo and microclimate.

Above-ground carbon storage is also impacted by afforestation and restoration. (Figure 2). The carbon fixation potential of a conifer crop is considerably greater than that of typical low-growing bog species. Although the above-ground carbon stock of typical bog vegetation may be non-trivial (Lindsay 2010) this is likely to be substantially exceeded by the above-ground carbon stock of a mature conifer plantation. It is currently unclear whether carbon fixation by the trees counteracts probable carbon loss from the peat. There is no published ecosystem-scale flux monitoring dataset for any UK afforested peatland and the consequent uncertainty is clearly reflected in the voting from project participants. A key issue in future studies will be the timescale under consideration. The greenhouse gas balance is likely to be very different between the period immediately following afforestation and plantation maturity and is likely to further vary across multiple cycles of restocking. Measurements of carbon fluxes alone will not provide a complete answer to the question as the ultimate climatic consequences of peatland forestry will also depend on the fate of timber from peatland plantations. If timber is left to rot or immediately burned then the carbon will be returned to the atmosphere rapidly. The argument is less clear if the timber is used for longer life-time uses, such as in construction, when it may take a century or more for the carbon to be returned to the atmosphere. The issue is even further complicated by the role of timber in the supply chain. Timber may compete with fossil fuels as a fuel source and with carbon-intensive materials such as concrete, steel and plastics in manufacturing and construction. Domestic UK timber production may avoid transport emissions associated with timber imports. A truly comprehensive greenhouse gas budget will require a detailed analysis of this complete supply chain, which is currently lacking.

The second question specifically highlights restoration as one future option. As for afforestation and restocking, it is possible to theorise some probable mechanisms but there is a lack of empirical data. Removal of trees will remove a large pool of above-ground carbon but the fate of this carbon will depend on subsequent timber usage. The process of felling and peat dam construction is likely to lead to some short-term increase in CO_2 flux due to disturbance of surface peat and decomposition of tree material not removed from site. In the longer term it can be expected that raising the water table will substantially reduce CO_2 emissions due to reduction in the oxic depth. This may be at least partially offset by increased emissions of CH_4, particularly in the early stages of rewetting, and where species with aerenchyma such as *Eriophorum angustifolium* become abundant (Morison 2012). As peatland vegetation becomes re-established, carbon sequestration will resume and should eventually lead to new peat formation if other conditions are suitable. While these processes are understood, the magnitude and timing of change are not, and the climatic benefits of forest-to-bog restoration are currently unclear. Carbon flux studies along restoration chronosequences, linked to process-based modelling, will be required to provide a sounder understanding.

The first of the two nominated questions specifies differences between forestry on peat and forestry on mineral soils and between forestry on deep and shallow peat. Forestry on mineral soils is known to represent net carbon sequestration. There is substantial carbon accumulation in the trees and this will more than outweigh any carbon loss from soils which, depending on the previous land use, may even experience an increase in carbon content (Korkanç 2014). It is clear that forestry on mineral soils is more effective than forestry on peat in terms of climate change mitigation, although the scale of the difference is currently impossible to quantify and will require more data collection from afforested peatland sites to compare with established datasets from mineral soils. The second element of the question addresses differences between forestry on deep and shallow peat. There has been no direct study of this topic and answers are likely to partially reflect what exactly is meant by deep and shallow peat. An answer to this question is currently not available although it is a reasonable assumption that forestry on shallow peat is more likely to have a net cooling effect than forestry on deep peat (Vanguelova *et al.* 2018).

Is it possible to have trees on peat without loss of biodiversity and carbon storage? (equal 2nd)

There are many examples of trees growing naturally on peat and forming ecosystems that support biodiversity and sequester carbon. Forested peatlands are widespread around the world, with coniferous trees across the boreal realm and with broadleaved trees in the tropics. Even in the UK, trees do occur on peat in some lowland fen systems and river valleys ('wet woodlands') and a few fragments of pine bog woodlands, somewhat similar to boreal forested peatlands, occur in isolated areas principally in eastern Scotland (Anderson & Harding 2002). These naturally wooded peatlands host valued biodiversity, with bog woodlands being a priority habitat under Annex I of the European Union Habitats Directive (EC 2007). Such sites also appear to accumulate carbon, although there are limited primary data. Palaeoecological evidence implies that trees on peat might once have been more prevalent in the UK (Birks 1975).

However, the intent of the voters selecting this question was probably more specific. The key issue is not whether wooded peatlands which both accumulate carbon and have biodiversity value *can exist* but whether they can be *created*. In Scotland, recent policy advocates the creation of 'Peatland Edge Woodland' in certain situations, with low density planting of native species within their natural ranges, most likely combined with rewetting of the peat surface (Forestry Commission Scotland 2015). Peatland Edge Woodland is the favoured option where there is no presumption to restore a site after felling, where tree growth is expected to be weak and there is potential for the establishment of 'predominantly native' woodland (Forestry Commission Scotland 2015). This policy is much disputed. Opponents fear that rather than achieving 'the best of both worlds', peatland edge woodland may actually be the 'worst of both worlds' with little or no biodiversity benefit (RSPB Scotland 2014), no timber production, and continued loss of peat carbon. There are also concerns that if not very actively managed, trees will come to dominate and a Peatland Edge Woodland will become similar to other secondary woodlands on peat, with a closed canopy and potential loss of peat carbon.

Two central issues in achieving any balance of tree cover with biodiversity and carbon storage are water table and feedbacks. Peatlands are too wet for most tree species to grow but lowering the water table leads to the increasing likelihood of carbon loss. Is there a middle ground in which trees can grow but carbon is retained? Secondly, trees on peat are not a passive component of the ecosystem. Trees tend to increase rainfall interception, increase evaporation, change albedo and increase transpiration, which will tend to dry the peat surface. There is a risk that this leads to a feedback whereby the presence of trees causes peat surface drying which results in more trees (Waddington *et al.* 2015). Whether optimum conditions which avoid these risks could be found is unclear. In relation to biodiversity there is also uncertainty and this will ultimately come down to which elements of biodiversity are prioritised. For many wading birds it is clear that any trees on the peatland surface will be negative, whereas birds such as black grouse, hen harrier and nightjar might benefit from trees at the correct density, age and species mix.

There is unlikely to be a simple answer to this question but several research directions could help address the theme. Peatland Edge Woodland sites in Scotland provide a timely opportunity to assess whether it is possible to avoid tree domination and will require close monitoring. Improved modelling of the tree-cover feedback will be required to extend knowledge more broadly. Future research could also address how carbon accumulation in naturally forested sites compares to that in open sites. Has tree cover been continuous or intermittent? What are the conditions which have allowed trees to persist on these sites without major negative consequences? These questions could be addressed through a combined approach linking contemporary ecology and the palaeoecological record.

What are the limits to the achievability of forest-to-bog restoration in terms of factors such as peat condition, depth and site extent?(equal 4th)

The IUCN peatland programme's recent draft peatland strategy increases its overarching restoration goal to achieving two million hectares of peatland in good condition, under restoration agreements and being sustainably managed by 2040 (IUCN UK PP 2018). Meeting such ambitious targets may not be possible simply by focusing on the relatively easy-to-restore 'low-hanging fruit' and may require more challenging sites to be tackled. A standard suite of methods for restoring afforested peatlands is reasonably well established and novel approaches are continually being developed. Most of this progress has been made on a trial-and-error basis by individual restoration managers and this knowledge has largely been communicated through informal and semi-formal networks.

In narrow terms of preventing rapid peat oxidation it can probably be expected that, as long as some peat remains and sufficient time is allowed, most peatlands degraded by afforestation are capable of restoration. The greatest challenges have arguably been presented by very cracked peats, but recently developed methods appear to be effective even for these (Anderson 2017). It is likely that innovation will continue to proceed through a process of trial and error, increasing the chances of success. Perhaps more important than what is technically possible is what is economic and practical, and here there is greater uncertainty and a need for thorough evaluation. The most important specific need is probably for better monitoring of restoration outcomes which is currently fragmented, impairing ability to conclusively establish the optimum methods.

What is the financial value of natural capital in natural and afforested peatlands and how does this change with restoration? (equal 4th)

The question reflects increasing interest in the natural capital concept amongst policy makers and attempts to place financial value on this capital under alternative land management options (eftec 2015). Peatlands supply and control many ecosystem services, some with obvious monetary value such as avoidance of water quality degradation and the consequent need for expensive additional treatment. It is more difficult to assign a monetary value to other ecosystem services, such as cultural services. We are aware of little research which has explicitly attempted to financially value ecosystem services and natural capital in UK peatlands, but it can be reasonably assumed that this value is considerable. For instance, applying the (UK pounds) carbon price as CO_2 equiv. recognised by the UK government (£4.19 t^{-1}; BEIS 2018 central series) to the likely carbon stock of UK peatlands (~ 3000 Mt; Lindsay 2010) yields a 'back of the envelope' valuation of at least £46 billion, equivalent to roughly 2.5 % of UK gross domestic product (IMF 2018). One valuation exercise for England values the risk of degraded peatland to an equitable climate at £70–210 million per year (eftec 2015). England contains in the order of 10–20 % of UK peatland (JNCC 2011) so, were all UK peatlands similarly degraded to those of England, their equivalent value might be up to ~ £2.1 billion per year. There is little extant data on valuation of other peatland ecosystem services. The value of forestry is more firmly quantified (> £8.5 billion; Timber Trade Federation 2017) but it is not clear what fraction of this economic activity relates to peatlands. Uncertainty in the extent of forestry on peat is compounded by the significant differences in productivity and economic value of forestry on peat versus mineral soils.

In the context of peatland restoration, Martin-Ortega *et al.* (2017) consulted the public in Scotland on the perceived value of peatland restoration, arriving at a range of £127–414 ha^{-1} yr^{-1} for benefits to carbon, water and wildlife. Moxey & Moran (2014) provide perhaps the most comprehensive assessment of the economics of peatland restoration, investigating a range of scenarios and concluding that carbon emissions savings are likely to be sufficient to justify restoration in the majority of cases. However, this study also found that results were very sensitive to assumptions around future emissions changes and these assumptions are particularly large for afforested peatlands.

Thus, the available evidence implies that peatland natural capital has significant economic value and is likely to change with afforestation and restocking, but quantitative valuation will require a thorough and systematic analysis, alongside answers to the other questions raised in this project.

CONCLUSIONS

There is currently considerable uncertainty around the future of UK afforested peatlands, and opinions on the best courses of action diverge (Payne *et al.* 2018). This project has highlighted very significant evidence gaps which are recognised by the community as important and are currently impairing decision-making. The situation is particularly acute because conifer afforestation of typically treeless blanket bogs is largely a UK and Ireland phenomenon. Although there is a substantial body of evidence on peatland forestry from other locations (particularly Fennoscandia), this is largely non-transferrable to the UK situation due to fundamental differences in the ecosystems and forestry practices (Lindsay 2010). Participants in this project highlighted a number of topics for which very limited fundamental data currently exist; with the climate change implications of afforestation, restocking and restoration pre-eminent in both nominated questions and final voting. The questions identified here form focal points for future research. Some key needs include:

- complete greenhouse gas budgets for sites along chronosequences of restoration and afforestation, and with differing peat depths;
- complete lifecycle analyses of peatland wood products;
- better understanding of the ecology, palaeoecology and carbon cycling of naturally wooded peatlands under UK conditions;
- better monitoring of peatland restoration outcomes based on currently-used restoration methods; and
- natural capital valuations for open, afforested and restored peatlands of various ages.

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AUTHOR CONTRIBUTIONS

The project was conceived by RJP and designed and implemented by WJ and RJP. Both authors contributed to writing the paper.

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